Why Quasar Pairs Are Binary Quasars And Not Gravitational Lenses

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ABSTRACT

We use simple comparisons of the optical and radio properties of the wide separation ($3'' < \Delta\theta < 10''$) quasar pairs to demonstrate that they are binary quasars rather than gravitational lenses. The most likely model is that all the pairs are binary quasars, with a one-sided 2–σ (1–σ) upper limit of 22% (8%) on the lens fraction. Simple models for the expected enhancement of quasar activity during galaxy mergers that are consistent with the enhancement observed at low redshift can explain the incidence, separations, redshifts, velocity differences, and radio properties of the binary quasar population. Only a modest fraction ($\lesssim 5\%$) of all quasar activity need be associated with galaxy mergers to explain the binary quasars.

Subject headings: Quasars — radio galaxies — gravitational lensing — binary quasars — galaxy mergers

1. Introduction

Of the $\sim 10^4$ known quasars (see, e.g., Hewitt & Burbidge 1993), we know of only ~ 40 quasar pairs or multiples with separations smaller than $10''$, most of which are confirmed gravitational lenses (see Keeton & Kochanek 1996).[1] Almost all of the confirmed lens systems have separations smaller than $3''$ and are produced by relatively isolated, normal galaxies (see Keeton, Kochanek & Falco 1997). Only 3 clear cases of multiple imaging by groups or clusters are known (Q 0957+561, Walsh et al. 1979; HE 1104–1805, Wisotzki et al. 1993; and MG 2016+112, Lawrence et al. 1984) and in all 3 cases there is at least one normal

[1] A current summary of the lens data is available at `http://cfa-www.harvard.edu/glensdata`.

galaxy associated with the primary lens. The remaining objects are wide-separation quasar pairs ($3'' < \Delta\theta < 10''$), with similar (but not identical) optical spectra, and small velocity differences ($|\Delta v| \lesssim 10^3$ km s^{-1}) that lack a normal group or cluster of galaxies to act as the lens. In the Large Bright Quasar Survey (LBQS) there are 2 quasar pairs in a sample of 10^3 quasars, so the probability of finding an optically-selected quasar pair is $P_{pair} \sim 2 \times 10^{-3}$ (see Hewett et al. 1997). We get about the same value if we note that 11 pairs have been found in a total sample of $\sim 10^4$ quasars, but the estimate from the LBQS has the advantage of uniform selection criteria. The pair fraction is two orders of magnitude higher than naively predicted from the quasar-quasar correlation function on Mpc scales (see Djorgovski 1991).

These problematic pairs have wreaked havoc on any quantitative discussion of gravitational lensing by group and cluster mass objects for over a decade. Determining whether these systems can be lenses is important because they require a previously unknown class of dark mass concentrations as the lens, and because the incidence of wide separation lenses is closely related to the amplitude of the power spectrum on $8h^{-1}$ Mpc scales (i.e. σ_8). Standard cosmological models normalized to COBE or the local cluster abundance predict few wide separation lenses (e.g. Narayan & White 1988; Cen et al. 1994; Wambsganss et al. 1995; Kochanek 1995; Tomita 1996; Flores & Primack 1996; Maoz et al. 1997) and require that most of the wide separation quasar pairs be binary quasars rather than gravitational lenses. The pairs also lead to bizarre results about the structure of lenses if they are simply treated as gravitational lenses (e.g. Park & Gott 1997; Williams 1997).

We list the known wide-separation quasar pairs in Table 1, and Figure 1 shows their distribution in separation and redshift. We have classified the pairs in two ways. First, we have divided the sample into the definite lenses, the definite binary quasars, and the ambiguous pairs. We can be certain a quasar pair is a lens if the optical and radio flux ratios are consistent, the velocity difference between the quasars is consistent with zero, and we see a plausible lens candidate. With these criteria we find the three quasar lenses with separations larger than $3''$ from the first paragraph: Q 0957+561, MG 2016+112, and HE 1104–1805. We can be certain a quasar pair is a binary quasar if there is no plausible lens candidate and the optical and radio flux ratios are grossly discrepant (PKS 1145–071, MGC 2214+3550, and Q 1343+2640), or if there is no plausible lens candidate and there is a significant emission line redshift difference confirmed by an absorption feature at the same velocity in the spectrum of the foreground object (Q 0151+048=PHL 1222=UM 144). The remaining 10 objects lie between these two regions of certainty: they lack a plausible lens galaxy, the optical and radio flux ratios do not grossly conflict, the velocity differences are small or depend only on emission line centroids, and the spectra show various levels of differences in their continuum and emission line structures. We tried to be extremely conservative in assigning objects to the binary quasar class, and we deliberately ignored strong evidence that several other

pairs are binary quasars (e.g. MG 0023+171 whose morphology is inconsistent with lensing, and HS 1216+5032 in which only one of the quasars is a BAL quasar, Q 1120+0195 which has a significant velocity difference, and Q 0151+048, Q 1120+0195, LBQS 1429–008, and LBQS 2153-2056 which have highly unlikely flux ratios for gravitational lenses). Second, we can classify the pairs based on their optical and radio properties: systems in which both quasars are radio-faint (O^2 pairs), systems in which one quasar is radio-bright (O^2R pairs), and systems in which both quasars are radio-bright (O^2R^2 pairs). We call a quasar radio-bright if it is detected in the radio at a given flux limit, and radio-faint if it is undetected, rather than radio-loud and radio-quiet (which are defined by the ratio of optical and radio fluxes). Where radio data were not already available, we searched for the pairs in the FIRST (White et al. 1997) and NVSS (Condon et al. 1996) surveys at 20 cm and 21 cm. We discovered that Q 1343+2640 is in fact an O^2R pair, but that the remaining O^2 pairs are all radio-faint to the NVSS catalog limits of ~ 3 mJy. By definition, lenses can only be O^2 or O^2R^2 pairs, and all O^2R pairs must be binary quasars.

We will not argue about whether any individual ambiguous pair is a gravitational lens or a binary quasar. Although observations and debates on these pairs are worthwhile, it is fair to say that detailed optical examinations of individual pairs have so far failed to produce convincing evidence for either the lens or the binary hypothesis once the possibility of "dark lenses" is accepted.[2] Instead, we show in §2 that the gravitational lens hypothesis makes predictions about radio properties of the quasar pairs that disagree with the data, while the binary quasar hypothesis naturally reproduces the data. In §3 we outline the relationship between quasars and galaxy mergers needed to explain the prevalence of binary quasars, and in §4 we discuss the implications of our conclusions.

2. Why Quasar Pairs Cannot Be Lenses And Must Be Binaries

There are two independent lines of argument that force us to conclude that the wide-separation quasar pairs are binary quasars. The first is the absence of an O^2R^2 quasar pair population comparable to the O^2 population, and the second is the existence of the three O^2R binary quasars. We first outline the two arguments, and then set a statistical upper limit on the fraction of the quasar pairs that can be gravitational lenses.

Under the lens hypothesis, the absence of a population of O^2R^2 quasar pairs is very

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[2]An illustration of the difficulty was our internal debate over whether Q 1120+0195=UM 425 deserved a "?–" designation as a pair with strong evidence suggesting it is a binary rather than a lens. EEF and JAM opposed the designation (see Michalitsianos et al. 1997).

Table 1. Wide Separation Quasar Pairs

Name	z_s	$\Delta\theta$	R (h_{50}^{-1} kpc)	Δm	f_R	$\lvert\Delta v\rvert$ (km s^{-1})	Lens?	Type	Ref
MG 0023+171	0.95	$4\farcs8$	40	1.2	~ 10	292 ± 260	?–	O^2R^2	1
Q 0151+048†	1.91	$3\farcs3$	28	3.6		520 ± 160	No	O^2	2
QJ 0240–343	1.41	$6\farcs1$	52	0.8		250 ± 180	?	O^2	3
RXJ 0911.4+0551	2.80	$3\farcs1$	24	0.7		158 ± 1000	?	O^2	4
Q 0957+561	1.41	$6\farcs1$	52	0.2	1.3	200 ± 15	Yes	O^2R^2	5
HE 1104–1805	2.32	$3\farcs1$	24	1.7		300 ± 90	Yes	O^2	6
Q 1120+0195††	1.46	$6\farcs5$	56	5.6		628 ± 120	?–	O^2	7
PKS 1145–071	1.35	$4\farcs2$	36	0.8	> 500	200 ± 110	No	O^2R	8
HS 1216+5032	1.45	$9\farcs1$	78	1.8		260 ± 1000	?–	O^2	9
Q 1343+2640*	2.03	$9\farcs5$	78	0.1	> 57	120 ± 890	No	O^2R	10
LBQS 1429–008	2.08	$5\farcs1$	42	3.1		260 ± 300	?–	O^2	11
Q 1635+267	1.96	$3\farcs8$	32	1.6		33 ± 86	?	O^2	12
MG 2016+112	3.27	$3\farcs6$	26	0.6	~ 1	40 ± 100	Yes	O^2R^2	13
Q 2138–431	1.64	$4\farcs5$	38	1.2		0 ± 115	?	O^2	14
LBQS 2153–2056	1.85	$7\farcs8$	64	2.9		1100 ± 1500	?–	O^2	15
MGC 2214+3550	0.88	$3\farcs0$	26	0.5	> 42	148 ± 420	No	O^2R	16
Q 2345+007	2.15	$7\farcs3$	58	1.5		476 ± 500	?	O^2	17

Note. — z_s is the source redshift, $\Delta\theta$ is the angular separation, R is the projected separation at the source redshift for $\Omega_0 = 1$ and $H_0 = 50h_{50}$ km s^{-1} Mpc^{-1}, Δm is the magnitude difference of the images, f_R is the radio flux ratio or its limit if at least one quasar is radio-loud, and $|\Delta v|$ is the velocity difference between the quasars. The entries in the Lens? column are: "Yes" if a normal lens (galaxy, group, or cluster) is seen in the correct position to produce the observed system, there is no significant velocity difference, and the radio and optical data are consistent with the lens hypothesis; "No" if we see no lens and either the radio emission or the emission line velocity difference, confirmed by an absorption line velocity difference, are inconsistent with the lens hypothesis; and, "?" if we see no lensing object but have no objective criterion to decide whether or not the object is lensed. If there is some evidence that the system is actually a binary, we used the label "?–". Type denotes the optical/radio classification of the pair. Note that MG 2016+112 is really a triple system, not a pair.

†Q 0151+048 is also named PHL 1222 and UM 144.

††Q 1120+019 is also named UM 425.

* We discovered that the brighter quasar is an 8.6 mJy source at 20 cm, and the FIRST survey detection limit at the location of the fainter quasar is 0.15 mJy, leading to a limit on the radio flux ratio of 57:1 as compared to an optical flux ratio of 1:1, making Q 1343+2640 an O^2R pair.

References: (1) Hewitt et al. 1987, (2) Meylan et al. 1990, (3) Tinney 1995, (4) Bade et al. 1997 (5) Walsh et al. 1979, (6) Wisotzki et al. 1993, (7) Meylan & Djorgovski 1989, (8) Djorgovski et al. 1987, (9) Hagen et al. 1996, (10) Crampton et al. 1988, (11) Hewett et al. 1989, (12) Djorgovski & Spinrad 1984, (13) Lawrence et al. 1984, (14) Hawkins et al. 1997, (15) Hewett et al. 1997, (16) Muñoz et al. 1997, (17) Weedman et al. 1982.

puzzling because the radio lens surveys (e.g. Burke, Lehàr & Conner 1992; King & Browne 1996; Browne et al. 1997) have in fact found the majority of gravitational lenses. If we inventory the gravitational lenses with image separations smaller than $3''$, we know of 30 gravitational lenses whose sources are quasars or radio sources (see the summary in Keeton & Kochanek 1996). Twelve of these lenses are radio-faint quasars, and 18 are radio sources of which at least 8 are radio-bright quasars. The ratio of the numbers of radio and optical lenses at small separations, $r_s = 1.5$, should be maintained at larger separations given the comparable redshift distributions and assuming similar angular selection functions. The radio lens surveys have fairly uniform selection functions out to $30''$, and should have higher completeness than the optical quasar surveys rather than the reverse. For example, given the one certain O^2 lens (HE 1104–1805) we would expect $r_s = 1.5$ O^2R^2 lenses, while we found two (Q 0957+561 and MG 2016+112). The scaling works well, with a "Poisson likelihood" of 25%. If we take the 9 ambiguous O^2 pairs and interpret them all as "dark" gravitational lenses, we would expect to find $9r_s = 13.5$ "dark" radio lenses. We in fact found only one (dubious) candidate, MG 0023+171, which has a Poisson likelihood $\sim 10^{-5}$. A nearly equivalent calculation is to note that the radio lens surveys have examined approximately 10^4 sources of which 25–50% will be high redshift quasars. If the number of radio-bright quasars is $N_{Rqso} \sim 5000$, then we should find $P_{pair}N_{Rqso} \simeq 10$ "dark" O^2R^2 quasar lenses. Again, we find only the one candidate, so the Poisson likelihood is $\sim 5 \times 10^{-4}$. Here we counted only lensed radio quasars rather than all radio lenses, leading to a modestly weaker limit. Since the completeness of the radio surveys is greater than that of the optical surveys, we have understated the case against the lens interpretation.

The key difference between the gravitational lens and binary hypotheses is that in the binary hypothesis we must introduce the low probability that a quasar is radio-bright into the calculation – only $P_{R30} \simeq 5\%$ ($P_{R1} \simeq 10\%$) of quasars are radio sources at 3.6 cm radio fluxes above 30 (1) mJy (Hooper et al. 1996; Bischof & Becker 1997). If we start from a sample of 11 optically selected quasar pairs, we should find that only $11P_{R1}^2 = 0.1$ of them are O^2R^2 pairs at a flux limit ~ 1 mJy, consistent with finding none to the NVSS flux limit of 2.5 mJy at 21 cm.[3] In the radio surveys, the expected number of binary quasars in the sample is still $P_{pair}N_{Rqso} \simeq 10$, but the radio surveys only discover the binaries in which both components are radio-bright at 3.6 cm fluxes $\gtrsim 30$ mJy. Thus the expected number of O^2R^2 binaries, $P_{R30}P_{pair}N_{Rqso} \simeq 0.5$, is smaller by a factor of P_{R30} and is consistent with the discovery of only one candidate (MG 0023+171).

[3]For the flat radio spectra typical of radio-bright quasars, a 20 cm flux of 2.5 mJy corresponds to a 3.6 cm flux of 1–6 mJy. The fraction of radio-bright quasars varies slowly with radio flux, so a lack of precision in the flux limits has little effect on the estimates.

The existence of the O^2R pairs is an equally important, independent argument against the lens hypothesis, because there should be no O^2R pairs in the absence of a larger O^2 binary quasar population. The relative numbers of O^2, O^2R and O^2R^2 binary quasars should be $(1-P_{R1})^2$, $2P_{R1}(1-P_{R1})$ and P_{R1}^2. Thus for 11 optically selected quasar pairs we would expect 2 O^2R pairs at a ~ 1 mJy flux limit, and we found one (Q 1343+2640), for a Poisson likelihood of 27%. The radio surveys should contain $(1-P_{R30})P_{pair}N_{Rqso} \simeq 10$ O^2R pairs, but they can only be found in optical follow up studies: PKS 1145–071 was discovered in an optical search for multiple (lensed) images, and MGC 2214+3550 was discovered as part of a redshift survey of radio sources which routinely took spectra of primary and secondary candidates for the optical counterpart of the radio source. The fraction of the radio sources that have undergone some type of optical follow up study that could detect an O^2R pair is roughly $\epsilon_{opt} \sim 10\%$. We expect to find $\epsilon_{opt}(1-P_{R30})P_{pair}N_{qso} \simeq 1$ O^2R pairs in the existing data, so the discovery of two such pairs has a Poisson probability $\sim 18\%$. Thus, the binary hypothesis naturally explains the O^2R pairs while they should not even exist under the gravitational lens hypothesis.

So far, we have made the calculations assuming all pairs are either lenses or binaries and found that the data strongly support the binary hypothesis. We now combine these arguments to estimate the fraction f_L of quasar pairs that are gravitational lenses. The optically selected pair sample consists of $11f_L$ lenses and $11(1-f_L)$ binary quasars. First, given the 11 optically selected pairs, we expect to find $11f_Lr_s = 16.5f_L$ "dark lenses" in the radio surveys, while with probability f_L we found one and with probability $1-f_L$ we found zero for the cases of treating MG 0023+171 as a lens or a binary. Second, the binaries in the optical sample should be divided as $11(1-f_L)(1-P_{R1})^2 = 10(1-f_L)$ O^2 binaries, $22(1-f_L)P_{R1}(1-P_{R1}) = 2(1-f_L)$ O^2R binaries, and $11(1-f_L)P_{R1}^2 = 0.1(1-f_L)$ O^2R^2 binaries, while the optically-selected data consist of at least one O^2 binary, one O^2R binary and no O^2R^2 binaries for a flux limit ~ 1 mJy. Third, given $N_{Rqso} \sim 5000$ radio quasars we expect $P_{R30}P_{pair}N_{Rqso}(1-f_L) \simeq 0.5(1-f_L)$ O^2R^2 pairs for a flux limit ~ 30 mJy, and we found either zero with probability f_L or one with probability $1-f_L$ depending on the treatment of MG 0023+171. We also expect $\epsilon_{opt}(1-P_{R30})P_{pair}N_{Rqso}(1-f_L) \simeq (1-f_L)$ O^2R pairs and we found 2. We then compute the likelihood distribution for f_L assuming a uniform prior. The maximum likelihood value is that all objects are binaries ($f_L = 0$) with a one-sided 2–σ (1–σ) Bayesian upper limit of $f_L < 22\%$ (8%).

The result is robust even though our calculation includes a number of crudely estimated parameters. For example, if we strongly bias the parameters to favor the lens hypothesis, by halving r_s and doubling N_{qso} and ϵ_{opt}, the 2–σ (1–σ) upper limits only shift to $f_L < 40\%$ (14%). If we drop the constraint from the expected number of "dark" radio lenses, and only determine the lens fraction consistent with the numbers of O^2R pairs, we find $f_L < 69\%$

(38%) at 2–σ (1–σ). In this model the maximum likelihood value for the lens fraction is still $f_L = 0$, but our limits are greatly weakened by our ultra-conservative division of the sample into binaries and ambiguous pairs.

There are several additional peculiarities to interpreting the O^2 pairs as a lensed population. First, the two wide-separation radio lenses have normal objects as lenses. In fact, all lenses imaged by HST besides the ambiguous O^2 pairs show an obvious lens galaxy unless the quasar images are so bright as to prevent the detection of any reasonable galaxy due to the contrast (see the summary by Keeton et al. 1997). Second, bright quasar lenses should rarely show large flux ratios ($\gtrsim$ 1–2 mag depending on the magnitude, see Kochanek 1993) between the components, while four of the O^2 pairs show magnitude differences of more than 2.5 mag (Q 1120+019, Q 1429–008, Q 0151+048, LBQS 2153–2056). Third, a significant fraction (30–40%) of the small separation lenses are four-image rather than two-image lenses, while we find no four-image wide-separation lenses. The counterargument here is that the lack of wide-separation four-image lenses is simply evidence that "dark lenses" have rounder potentials than galaxies. Fourth, the probability for producing lenses of a given separation rises monotonically with source redshift, although the probability will rise faster at small separations since the more massive lenses form at lower redshifts in standard models. Thus the concentration of all O^2 pairs near $z_s = 1$ to 2 is difficult to reconcile with the more uniform redshift distribution of the smaller separation lenses. The selection functions for finding lenses and pairs are reasonably uniform inside 6″ (the outer radius checked by most optical lens surveys), so the rise in the ratio of small separation quasar lenses to O^2 pairs from 1:1 to 4:1 between $z = 2$ and $z = 3$ (see Fig. 1) is strong evidence against the lens hypothesis.

3. Consequences of the Binary Hypothesis

The standard criticism of the binary quasar explanation for the quasar pairs was clearly stated by Djorgovski (1991). For a comoving bright quasar density of $n_q \simeq 500h_{50}^3$ Gpc^{-3} (Hartwick & Schade 1990) and a correlation function $\xi(r) = (r/r_0)^{-1.8}$ with $r_0 \simeq (11 \pm 2)h_{50}^{-1}$ Mpc (Croom & Shanks 1996), the probability of finding a second quasar within projected separation $R = 50h_{50}^{-1}R_{50}$ kpc is $P_{q0} \sim 2 \times 10^{-5} R_{50}^{1.2}$. The observed probability of finding a close quasar pair of $P_{pair} \sim 2 \times 10^{-3}$ (e.g. Hewett et al. 1997) is a factor of $\sim 10^2$ larger. The enhancement is confined to very small spatial scales, because we should have found 20 times as many pairs between 10″ and 100″ as are found between 3″ and 10″ if the distribution simply followed the slope of the correlation function. Wide area surveys such as the LBQS have not found such a larger quasar pair population (given the 2 wide-separation quasar pairs

in the LBQS, they should have found 40 wider pairs!). Thus, the binary quasars correspond to merging galaxies with separations $\lesssim 50h_{50}^{-1}$ kpc rather than chance superpositions, and the fundamental flaw in using the correlation function argument against the binary hypothesis (as already noted by Djorgovski 1991) is that it fails to include the increased probability that a black hole will be an active quasar during a galaxy merger. In the local universe we see that nuclear activity (starbursts and AGN) is enhanced by mergers and interactions (e.g. Keel 1996; Bahcall et al. 1997). Theoretically, simulations of merging galaxies (e.g. Barnes & Hernquist 1996) demonstrate that interactions drive gas toward the central regions of the galaxy where it can be used to fuel a new burst of activity in a previously quiescent galaxy. Far from being surprised, we should have predicted that binary quasars would be significantly more abundant than predicted by the correlation function on large (Mpc) scales.

Quasars are the active cores of galaxies, so to understand the clustering of quasars we should start from the clustering of the underlying galaxies. The quasar-quasar correlation function on large (Mpc) scales should be identical to the galaxy-galaxy correlation function; so for a comoving galaxy density n_g, the comoving density of galaxy pairs with separation smaller than r_a is

$$n_{g2} = 2\pi n_g^2 \int_0^{r_a} r^2 \xi(r) = 5.2 n_g^2 r_a^{1.2} r_0^{1.8} \tag{1}$$

provided the probability for a third galaxy in the volume is small (e.g. Peebles 1993). If the probability $f_{iso} \ll 1$ of an isolated galaxy having an active quasar is the same for all galaxies, then $n_q = f_{iso} n_g$ and the density of quasar pairs is $n_{q2} = f_{iso}^2 n_{g2}$. For a constant comoving galaxy density of $\sim 10^6 h_{50}^3$ Gpc^{-3} (e.g. Marzke et al. 1994; Loveday 1992) we find $f_{iso} \sim 5 \times 10^{-4}$. The fraction of quasar pairs, $n_{q2}/n_q \simeq 5 f_{iso} n_{g2}/n_g \simeq 5 n_q r_a^{1.2} r_0^{1.8}$, with separations smaller than r_a is consistent with our earlier, direct estimate from the quasar-quasar correlation function. Suppose, however, that the probability of a galaxy having an active quasar when it is a member of a pair is $f_{merge} > f_{iso}$. The density of quasar pairs is now $f_{merge}^2 n_{g2}$, and the fraction of quasar pairs is larger by the factor $\beta^2 = (f_{merge}/f_{iso})^2$. Thus to explain the 10^2 overabundance of quasar pairs we need only a factor of $\beta = 10$ increase in the probability of quasar activity in merging systems over isolated systems.

At low redshift, it is known that the amplitude of the galaxy-quasar correlation function is larger than the amplitude of the galaxy-galaxy correlation function by a factor of 4 ± 1 (Fisher et al. 1997; Yee & Green 1987; French & Gunn 1983). Equivalently, the fraction of quasars with companion galaxies, $\beta n_{g2}/n_g$, is larger than the fraction of galaxies with companions, n_{g2}/n_g, by a factor of $\beta = f_{merge}/f_{iso}$. The correlation function comparisons average the galaxy density over volumes much larger than the physical scales on which tidal interactions provide a mechanism for increasing the amount of quasar activity, so the ratio of the correlation function amplitudes sets only a lower bound of $\beta > 4$. On small scales

we estimate enhancements of $\beta \sim 17$ (9) from the 2 companions brighter than L_* (or the 9 brighter than $0.1L_*$) found within $50h_{50}^{-1}$ kpc of the 20 bright, low-redshift quasars studied by Bahcall et al. (1997). As expected, the enhancement is larger than the limit derived from the correlation function measured over larger volumes. The amplitude of the enhancement is sufficient to explain the incidence of binary quasars in the high-redshift sample. Note that we do not expect any binary quasars in the Bahcall et al. (1997) sample because the expected number of binary quasars is smaller than the number of quasars with companion galaxies by a factor of $f_{merge} \sim 5 \times 10^{-3}$ for $f_{iso} \sim 5 \times 10^{-4}$ and $\beta = 10$.

Models of the history of quasars and supermassive black holes (Small & Blandford 1992; Haehnelt & Rees 1993) suggest that the enhancement in the number of binary quasars can be explained either by an increase in the formation rate of black holes, or by the reignition of existing black holes as quasars. The observed luminosity of the quasars is directly related to the final, total mass in supermassive black holes because the luminosity is set by the accretion rate, and the mean black hole mass per galaxy of approximately $10^7 M_\odot$ estimated from the total quasar luminosity is consistent with the results of direct dynamical observations of nearby galaxies (see Kormendy & Richstone 1995; Magorrian et al. 1997). At the Eddington limit, a black hole's mass increases by a factor of 10 in $t_{10} \simeq 10^8 \epsilon_1$ yrs, where ϵ_1 is the accretion efficiency in units of 10%. Since we do not find $10^{10} M_\odot$ black holes locally, and the bright quasars making up the pairs require 10^8–$10^9 M_\odot$ black holes fueled near the Eddington rate, t_{10} sets a maximum active lifetime for the black holes as bright quasars. The age of the universe ($t = t_0(1+z)^{-3/2}$ with $t_0 = (2/3)(c/H_0)$ for $\Omega = 1$) is much longer than the lifetime of any individual quasar since $t_0/t_{10} \simeq 130 h_{50}^{-1} \epsilon_1^{-1} (1+z)^{-3/2}$. Thus, the duty cycle, or probability that a massive black hole is functioning as a luminous quasar is only a few percent. At high redshift we can approximate the black hole formation rate by a constant rate of $\dot{n}_{BH} \simeq n_Q/t_{10}$, and the total number of massive black holes by $n_{BH} \simeq n_Q(t_0/t_{10})(1+z)^{-3/2}$. The quiescent black holes outnumber the quasars by a factor of $(t_0/t_{10})(1+z)^{-3/2}$.

The simplest general model for the formation of quasars during mergers is simply to add a density dependent term to the formation probability,

$$f \simeq f_{iso} + f_{merge}\xi\left(\max\left[r, r_a\right]\right). \tag{2}$$

If we allow the second term to saturate at $r_a \lesssim 50h_{50}^{-1}$ kpc and use the low-redshift enhancement factor of $\beta = f_{merge}/f_{iso} \sim 10$, mergers naturally explain the incidence of high redshift binary quasars. To the extent that formation and renewed accretion are qualitatively different processes, an alternate process is to form the binary quasars by reigniting extinct quasars during mergers. The probability of finding a black hole near a quasar is larger than the probability of finding a quasar by the factor $(n_{BH}/n_q) \gg 1$. If p_{ri} is the probability of

reigniting an extinct quasar, then $\beta = p_{ri} n_{BH}/n_q$, and

$$p_{ri} \simeq 10 \frac{t_{10}}{t_0} (1+z)^{3/2} \simeq 0.1(1+z)^{3/2}. \quad (3)$$

is sufficient to explain the numbers of binary quasars. In either case, only a few percent of all quasars are formed by the merger related processes, so they do not represent a significant change in the mean quasar formation history.

Unlike the gravitational lens hypothesis, the binary hypothesis naturally explains the concentration of the pairs between $1 \lesssim z \lesssim 2$. In both formation models the peak in the binary quasar redshift distribution should be near the peak in the quasar redshift distribution, with a comparable or narrower width. The density dependent formation model produces a peak at the same redshift, while the reignition model should have a peak at slightly lower redshift because the number of extinct quasars is higher on the low redshift side of the quasar peak. In the Boyle, Shanks & Peterson (1988) quasar luminosity function, the peak surface density at $B \simeq 19$ mag is at $z \simeq 2$ and 90% of the quasars lie at $z \lesssim 2.5$, very similar to the observed distribution of the pairs. Both models predict that binary quasars should be significantly rarer than gravitational lenses at $z > 2.5$ even though they are almost equally abundant at $z = 2$. The binary hypothesis also provides a natural explanation for the wide range of optical flux ratios seen in the quasar pairs. While it is unlikely for a lens system with a bright quasar image ($m \lesssim 19$ B mag) to have a large flux ratio, variations in the accretion rates and black hole masses provide a natural explanation for the broad range of flux ratios seen in the quasar pairs. If we drew the luminosities of the pairs randomly based on the luminosity function we would expect most binary quasars to show large flux ratios, constrained by the dynamic range limits of the quasar surveys (see Kochanek 1995). The common triggering mechanism for the quasar binaries may, however, produce luminosity correlations between the two quasars.

Like the gravitational lens hypothesis, the binary hypothesis naturally explains the separations of the pairs and the small velocity differences. The use of mergers to trigger more quasar activity requires characteristic separations $\lesssim 50 h_{50}^{-1}$ kpc. Although the pairs will tend to have larger separations than their orbital pericenters because they spend more time near apocenter, we should expect to find some binary quasars below $\Delta\theta = 3''$. The apparently sharp cutoff at separations larger than $10''$ may also be more characteristic of mergers than of gravitational lenses – statistical models of wide separation lenses (see Kochanek 1995; Wambsganss et al. 1995) that produce the observed numbers of pairs as lenses generally have a slowly declining distribution in separation. The velocity differences between the quasars should be characteristic of binary galaxies. For example, the mean pair-wise velocity dispersion in the CfA redshift survey is 295 ± 100 km s^{-1} if Abell clusters with $R > 1$ are excluded from the sample (Marzke et al. 1995), and the typical difference for Seyferts in

binary galaxy systems is 170±200 (Keel 1996), both of which are consistent with the observed velocity differences of the pairs.

4. Discussion

Our comparison of the optical and radio data rules out the pure gravitational lens hypothesis for the quasar pair population, and requires that most of the quasar pairs be binary quasars. However, it is a statistical argument about the population, and it cannot prove that any individual quasar pair is binary rather than a lens. On the other hand, once we demonstrate that most of the pairs must be binary quasars, Occam's razor suggests that they are all binary quasars, since the "dark lens" hypothesis now requires an entirely new population of objects with the masses of clusters but no stellar or X-ray luminosity to produce a few wide separation "dark lenses" that are essentially indistinguishable from a dominant population of binary quasars. The enormous consequences of even a modest population of "dark lenses" demands a high standard of proof before invoking the interpretation for any pair. If there are $\simeq 3$ lenses produced by a "dark lens" population (scaling from Wambsganss et al. 1995; Kochanek 1995) the comoving density of the "dark lenses" matches that of groups and clusters, the true value of σ_8 is significantly larger than estimated from the abundance of clusters, and many results in structure formation and about the shape and amplitude of the power spectrum become invalid.

The association of quasar activity with mergers is an old idea, as is the suggestion that the quasar pairs are related to merger activity (e.g. Djorgovski 1991). It is seen in the local universe where nuclear activity is more common in merging systems (e.g. Keel 1996; Bahcall et al. 1997), and it is expected from theoretical models of gas dynamics during mergers (e.g. Barnes & Hernquist 1996). In fact, the enhancement in quasar activity produced by mergers estimated from the number of galaxies seen near the Bahcall et al. (1997) quasar sample exactly matches the enhancement needed to explain the binary quasar population at high redshift. Furthermore, the merger model naturally explains all the features of the binary quasar population: (1) the separations are characteristic of scales on which tidal perturbations become important ($R \lesssim 50h_{50}^{-1}$ kpc); (2) the radio properties of the sample are explained by the low probability that quasars are radio-bright; (3) the relative velocities should be $\lesssim 10^3$ km s^{-1} because they are characteristic of merging galaxies; (4) the pairs should be concentrated in redshift at or below the peak in the quasar abundance.

While we avoided arguments about the interpretation of the individual, ambiguous pairs in our discussion, it is still important to examine the individual cases. The only simple test that can unambiguously prove that a quasar pair is a binary is to show that it is an O^2R

binary quasar using deep radio observations. For example, Patnaik, Schneider & Narayan (1996) discovered that Q 2345+007 A is a $\sim$ 30 μJy radio source. The B image was not detected, but the predicted flux was too close to the noise level to test the lens hypothesis. Nonetheless, similar observations of the other O^2 pairs should show that several of them are O^2R pairs since the fraction of quasars with detectable radio flux begins to rise below a 3.6 cm flux of 1 mJy. At 0.3 mJy the fraction of detectable quasars is 15% (Hooper et al. 1995), but little is known about the fraction of quasars with emission at $\sim$ 0.01 mJy (see Fomalont et al. 1991). Measuring a time delay is the only unambiguous test to prove that a pair is a "dark lens", although a strong case can also be made if there is a significant weak lensing detection centered on the pair. A weak lensing effect is detected near Q 2345+007 (Bonnet et al. 1993), but its center is too far from the pair to be responsible for the image splitting. The ambiguities in current arguments about spectral similarities would be greatly reduced by quantitative spectral comparisons between random isolated quasars, binary quasar members, lensed quasars and the ambiguous pairs. An initial study by Small, Sargent & Steidel (1997) showed that the emission line differences in Q 1634+267 and Q 2345+007 were consistent with the differences seen in the spectra of isolated quasars viewed at different times. However, such comparisons must account for two biases. First, in focusing on Q 1634+267 and Q 2345+007, Small et al. (1997) selected the quasar pairs already known to show smaller spectral differences than a randomly selected quasar pair. Second, a proper comparison of the spectra of the various object classes must also compensate for the possibility that binary quasars will be more similar than randomly selected quasar pairs simply because they have similar redshifts, luminosities, and environments.

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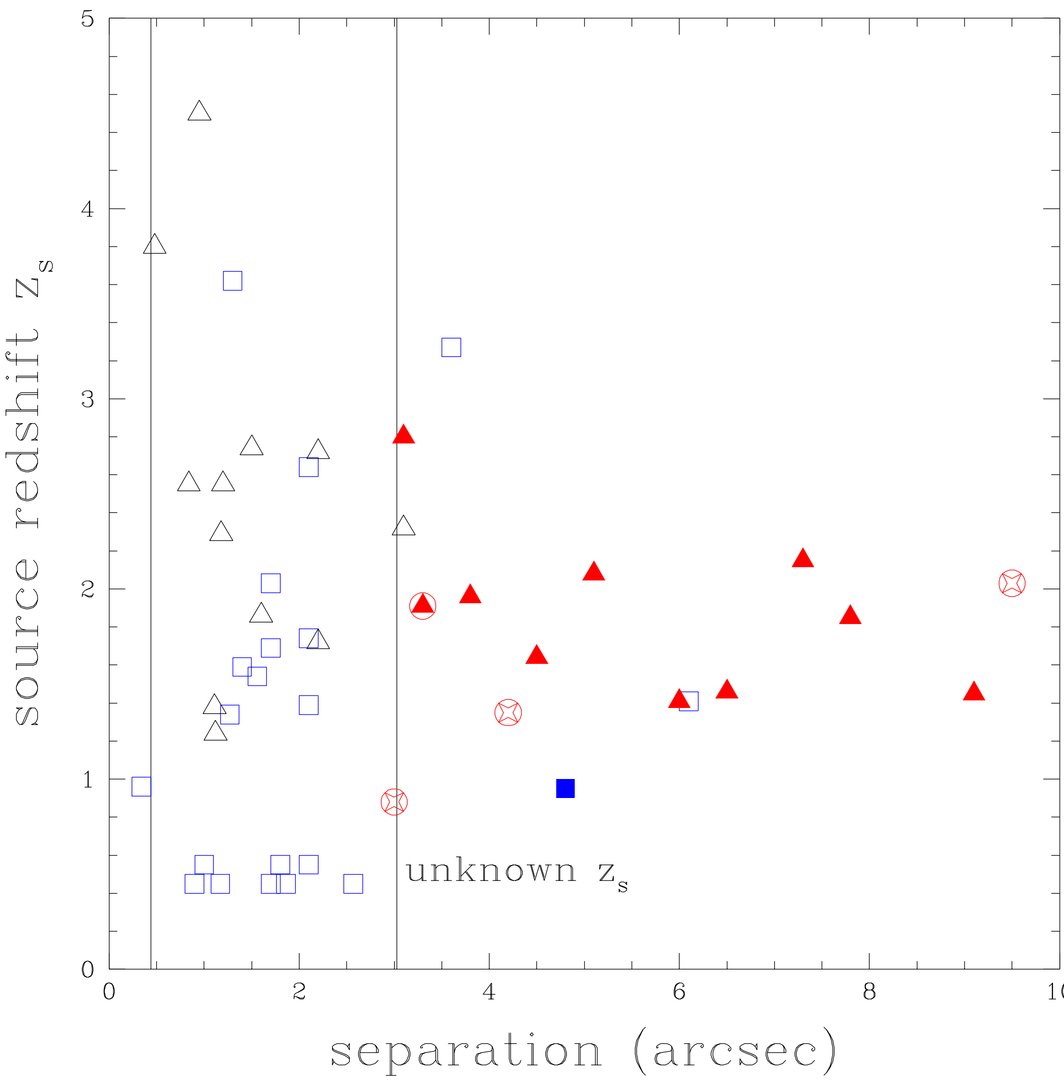

Fig. 1.— The distribution of pairs, binaries and lenses in separation and source redshift. Triangles are radio-faint lenses and O^2 pairs, stars are O^2R binary quasars, and squares are radio-bright lenses and O^2R^2 pairs. Open triangles and squares are certain lenses, filled triangles and squares are ambiguous pairs, and circled symbols are certain binaries. If early-type galaxies were the dominant lens population, 90% of lenses would lie between the two vertical lines. Radio lenses with unknown source redshifts are displayed in a band at $z_s = 0.5$, although we would expect their mean redshifts to be higher than for the lens systems with known source redshifts.